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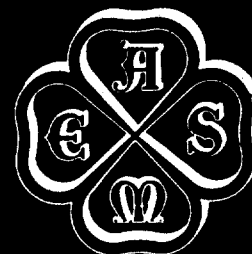
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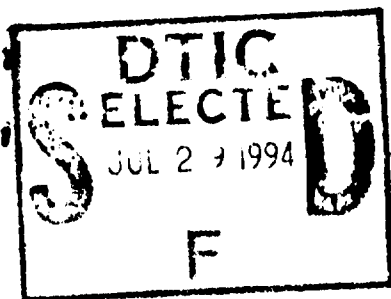
paper no.

56--A-111



HEAT TRANSFER BY RADIATION FROM FLAMES

R. A. Sherman, Fellow ASME
Technical Director
Battelle Memorial Institute
505 King Avenue
Columbus 1, Ohio



Contributed by the Heat Transfer Division for presentation at the ASME Annual Meeting, New York, N.Y. - November 25-30, 1956. (Manuscript received at ASME Headquarters August 9, 1956.)

Written discussion on this paper will be accepted up to January 10, 1957.

(Copies will be available until October 1, 1957)

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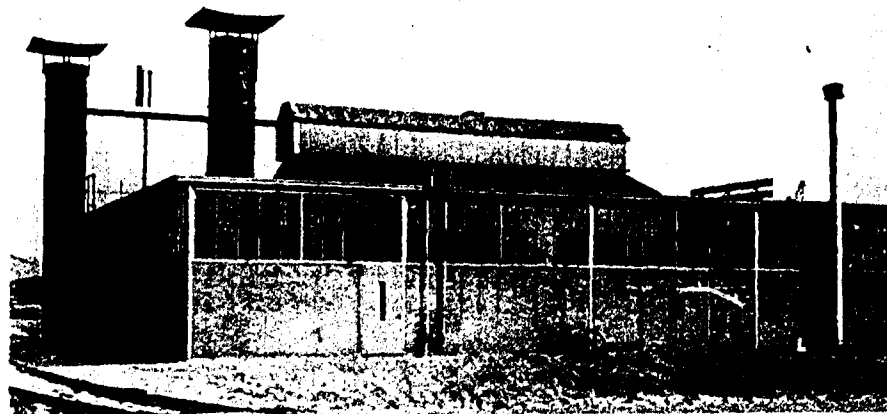
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Printed in U. S. A.

Heat Transfer by Radiation From Flames

*A Summary of the work
of the International
Flame Research Foundation*



By R. A. Sherman

FIGURE 1 VIEW OF THE LABORATORY

A unique example of international co-operation is given in the program of research on radiation from flames in industrial furnaces that is being conducted at the Royal Netherlands Blast Furnace and Steel Works. Financial support and direction came first from the Netherlands, France, and Great Britain. The countries have now been joined by Belgium, Sweden, the United States, and the High Authority of the European Community of Coal and Steel. This paper outlines the organization of the work, the experimental facilities, the methods of research, and presents the outstanding results on the effect of the variables studied on flame radiation. These variables have been the type of fuel oils or coke-oven gas, the rate of heat input, the type and rate of supply of atomizing agent, the type of burner, the excess of air, the type and amount of carbureting agent for gas, and the temperature of the combustion air. Of these several variables, the C/H ratio of the oil and gas fuels and the mixing conditions most markedly affect the emissivity and the radiation of the flames. The results point to the need for further knowledge of the relation of the radiating characteristics of flames to the rate of heat transfer to "work" in furnaces. The research has now been extended to include the use of pulverized coal.

In recognition of the need for greater knowledge of the transfer of heat by radiation from flames in industrial furnaces, Prof. J. E. de Graaf, then director of research, The Royal Netherlands Blast Furnace and Steel Works, initiated, shortly after World War II, an experimental program of research to fill this need. A tunnel furnace fired with a flame one fourth the linear dimensions of an open-hearth flame was built at the IJmuiden, Holland, plant by Prof. de Graaf and experimental work was started. Within a short time, word of the research reached France and England where it aroused considerable industrial interest, and arrangements were soon made whereby the industries of those countries were enabled to contribute both to the financial support and to the planning and execution of the experiments and to the analysis and publication of the results.

As early as 1951, interest from the United States was demonstrated, and in 1952, under the leadership of Prof. Hoyt C. Hottel of The Massachusetts Institute of Technology, an American Committee was formed for co-operation in the research. This committee has since been active in financial support of the program and in reviewing the results of the work. Sweden and Belgium have joined and the High Authority of the European Community of Coal and Steel in 1955 made a major financial contribution to the support of the work.

The story of this unique example of international co-operation--unique because it was the result of spontaneous activity on the part of scientists and engineers without governmental

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action--has been widely publicized in England and France, but, with the exception of a few notes and a brief paper by Prof. Thring (1),¹ no comprehensive account of the objectives, method of operation, or of the results has been published in the United States. This paper aims to furnish this account.

ORGANIZATION

In November, 1955, the International Joint Committee for Flame Radiation, prior to that time a rather informal and loosely knit organization, was formalized by its registration in Holland as the International Flame Research Foundation. Its objectives are the attainment of knowledge and experience on the combustion of gaseous, liquid, and solid fuel, in particular as the combustion aims at the heating of materials and the placing of that knowledge and experience at the disposal of others for further development and industrial application. The Foundation is of the not-for-profit type and is required by its charter to apply its income and property solely toward the promotion of its stated objectives.

The President of the Foundation, who had been from the beginning the chairman of the Joint Committee, is the eminent Prof. G. M. Ribaud, noted French physicist, and recently retired as director of research for the gas industry of France.

The General Superintendent of the research program is Prof. M. W. Thring, formerly Head of Physics Department, British Iron and Steel Research Association, and since 1953, Head of Fuel Technology, Sheffield University.

The governing body of the Foundation is the Joint Committee made up of two or more representatives of each national committee. The present membership of the Joint Committee is as follows:

Belgium:	P. Coheur, Professor, National Metallurgical Research Center, Liege
	G. A. Homès, Professor of Metallurgy, Universities of Mons and Brussels
France:	Raymond Cheradame, Director General, Research Center, Coal Industry of France, Paris and Verneuil

Henri Malcor, President,
French Institute for Iron
and Steel Research, Paris

Great Britain: O. A. Saunders, Professor,
Imperial College of Science
and Technology, London

D. T. A. Townend, Director
General, British Coal Utili-
zation Research Association,
Leatherhead

Netherlands: J. E. de Graaf, Professor,
Technological University,
Delft, and Technical Ad-
visor, Royal Netherlands
Blast Furnace and Steel
Works, IJmuiden

J. O. Hinze, Professor,
Technological University,
Delft

Sweden: O. G. Hammar, Professor,
University of Göteborg

America: F. S. Bloom, President,
Bloom Engineering Company,
Pittsburgh, Pennsylvania

E. G. Chilton, Research De-
partment, Shell Oil Company,
Emeryville, California

Ralph A. Sherman, Technical
Director, Battelle Memorial
Institute, Columbus, Ohio
(Alternate: Bertrand A.
Landry, Paris Branch, Bat-
telle Memorial Institute)

In addition, Professor Ribaud, Professor Thring, and P. A. H. Elliot, General Secretary, are members of the Joint Committee.

The Joint Committee holds meetings several times a year to decide on general policies. A Technical Advisory Committee, and special committees on Aerodynamics, on Pulverized Fuel, on Burners, on Furnaces, on Instruments, on Editing, and on Finances, bring to the planning and analysis of the work the best available talent for each phase.

The National Committees are autonomous and can obtain their financial support and can se-

¹ Numbers in parentheses refer to the Bibliography at the end of the paper.

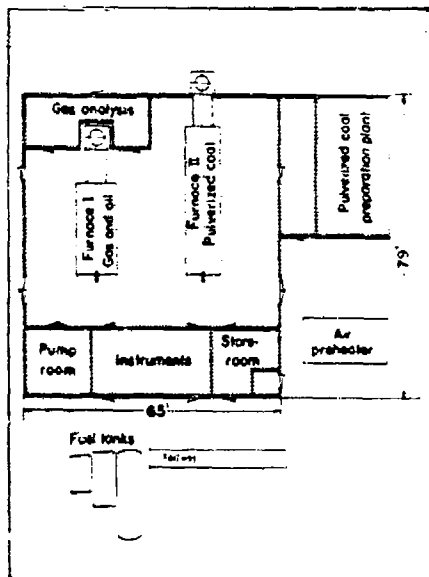


FIGURE 2. PLAN OF LABORATORY

lect their membership in any way that each group may decide proper. The financial contribution from each country may be suggested by the Joint Committee but the final decision is made for itself by each National Committee.

Although the original conception of the work was in a steel company and the experimental furnace was intended to have a reasonable similarity to an open-hearth steel furnace, the research is of such a basic nature that interest and support have come not only from the steel industry, but also from other sources including the boiler and fuel-equipment manufacturers, the glass industry, the cement industry, and from the coal, petroleum, and gas industries.

The execution of the work at IJmuiden is in charge of a Principal Investigator who was first British, then French, and is now, again British. The Joint Committee has for some time also paid for the services of another investigator, presently British, to work with Professor Hammar in Sweden on the fitting out of a new experimental furnace with cold walls at Göteborg. For the main experiments at IJmuiden, in which 30 to 40 men have been required for several weeks, investigators are furnished from co-operating companies in the several countries. Normally, their salaries and traveling expenses are borne by their employers; thus, there are, in addition to the cash contributions, substantial contributions "in kind."

Several companies and associations in England, France, and Holland have independently carried on research on flame radiation to supplement or to complement the work at IJmuiden. Much of the information so obtained has been made available to the Joint Committee or published separately in the literature.

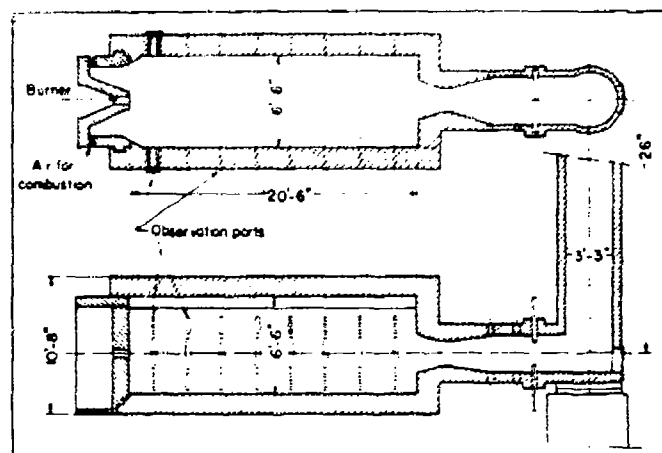


FIGURE 3. PLAN AND SECTIONAL ELEVATION OF GAS OR OIL FURNACE

As described below, the expenditures in the last three years for new facilities and equipment have been heavy, but the \$56,000 costs in 1955 are expected to be the last major expenditures of a capital nature. The total cost of the experimental furnaces and equipment now available at IJmuiden was approximately \$200,000. The operating costs in 1955 paid by the Joint Committee were approximately \$64,000, and the contributions "in kind" amounted to about \$25,000.

EXPERIMENTAL FACILITIES

The original experimental furnace and testing facilities installed by the Royal Netherlands Steel Works were used from the start of the work through 1953 for a series of seven sets of formal tests and much supplementary investigation. Since then, a new furnace for the gas and oil studies, housed in a permanent special building 65 x 79 ft, has been available. The building houses also rooms for gas analysis, instruments, fuel pumps, and supplies. In an attached, partly enclosed structure is a plant for the preparation of pulverized coal, and at one side is an air preheater.

Fig. 1 is a view of the laboratory. Fig. 2 shows the plan of the building.

Fig. 3 shows a plan and elevation of the gas or oil furnace which is of the same size and shape as the original furnace.

It is essentially square in transverse vertical section, 6-1/2 x 6-1/2 ft, and about 20 ft long from the burner to the furnace exit. The furnace is lined with a high-grade sillimanite refractory enclosed with insulating refractory and jacketed in a steel casing.

The gas or oil burners are installed on the

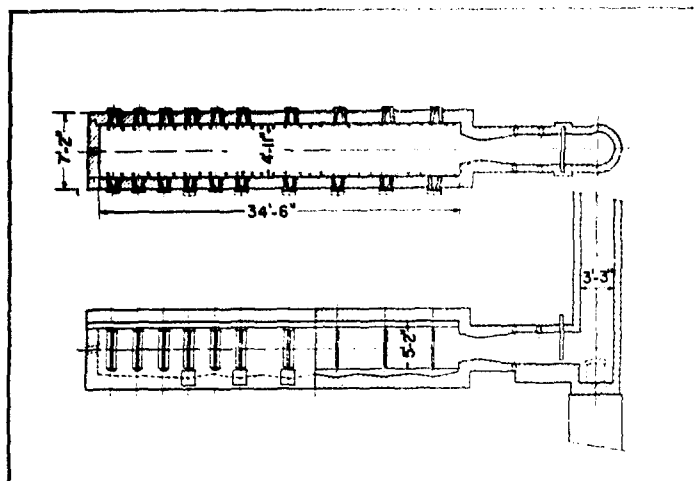


FIGURE 4. PLAN AND SECTIONAL ELEVATION OF PULVERIZED COAL FURNACE

Air for combustion is supplied by blowers. The air preheater, fired with blast-furnace gas, can heat the air to 1380 F. All rates of flow of fuel and air are closely controllable and are measured and recorded. Fig. 5 is a view of the instrument room showing the many recorders.

The range of heat input to the oil and gas-fired furnace has been 4 to 10 million Btu per hr, or approximately 4600 to 11,500 Btu per cu ft-hr.

In addition to the experimental furnaces described there is available at IJmuiden a smaller-scale water-cooled furnace which was designed, constructed, and operated for several years by the Royal Dutch Shell Company at its Delft Research Laboratories. Also a one-fifth scale

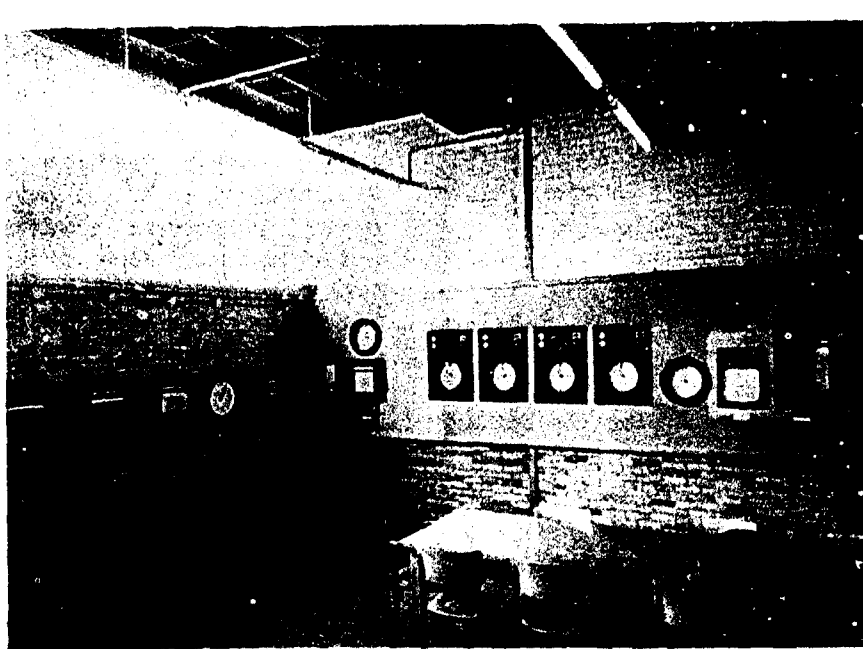


FIGURE 5 INSTRUMENT ROOM OF IJMUIDEN LABORATORY

center axis of the furnace at the nose of the "dog house". Secondary air is normally admitted at low velocity through ports in the walls at either side of the burner; mixing is by diffusion. Air also can be admitted around the burner if desired.

Fig. 4 shows plan and vertical sections of the second recently completed furnace designed especially for burning pulverized coal. It is of similar construction but is only 4 ft 11 in. x 5 ft 2 in. in transverse vertical section and is 34-1/2 ft long. Doors are provided on one side at the bottom for removal of ash. This furnace can be equipped with internal water cooling for the purpose of increasing the thermal load and thereby simulating a steam boiler.

model of each of the fuel-fired furnaces has been constructed of transparent plastic; these are used to study mixing patterns of fuel and air.

EXPERIMENTAL METHODS

To obtain data on the radiating characteristics of the flames, which is the principal objective of the research, a series of ports in the form of vertical slots is provided in one wall of each furnace. By an ingenious arrangement, the radio-meters can be moved up or down for a vertical traverse of the flame and the ports can be closed to avoid inleakage of air.

Three types of radiometers have been built and used. One consists of a thermopile mounted

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on the end of a water-cooled tube which contains a series of diaphragms to limit the field of view of the thermopile. The second type uses a fixed-focus rhodium-plated mirror to reflect the radiation onto a thermopile. A third type is based on this same principle but is designed to measure radiation from two sources simultaneously. Electrically heated, tube or sphere furnaces are used at frequent intervals for purposes of calibration of the radiometers.

In the wall opposite that through which the thermopiles are inserted is a vertical water-cooled slot. When the radiometer is sighted through the flame at this low-temperature surface, the radiation from the flame alone is received. By turning the radiometer through a small angle, it is sighted through the flame onto the opposite refractory wall in which a thermocouple at the inner surface measures the temperature. By the method developed by Schmidt (2), the emissivity of the flame may be calculated as follows:

$$e = \frac{R_1 - R_2 + R_3}{R_3}$$

Where e is the emissivity of the flame and R_1 is the radiation measured from the flame alone, R_2 is that from the flame and hot refractory wall, and R_3 is the radiation of the wall alone as calculated from the observed temperature assuming an emissivity of the wall of unity. This is a simple arithmetical relation inasmuch as

$$R_1 = \sigma e T_f^4$$

$$R_2 = \sigma e T_f^4 + (1-e) R_3$$

and

$$R_3 = \sigma T_w^4$$

where σ is the Stefan-Boltzmann constant and T_f and T_w are the absolute temperatures of the flame and wall, respectively.

Then

$$\frac{\sigma e T_f^4 - \sigma e T_f^4 - (1-e) \sigma T_w^4 + \sigma T_w^4}{\sigma T_w^4}$$

becomes

$$\frac{\sigma T_w^4 - \sigma T_w^4 + e \sigma T_w^4}{\sigma T_w^4}$$

which reduces to e . Having derived e , one obviously can derive a flame temperature as

$$T_f = \sqrt[4]{\frac{R_1}{\sigma e}}$$

This derivation assumes that the factor $(1-e)$ is equal to the transmissivity. This is true only for gray flames. It is true for nongray flames, such as nonluminous flames, only when the temperature of the wall is equal to the temperature of the flame which is not usually true. Hence, the emissivities and temperatures of the flames derived in this way can be considered only approximate.

In addition to these readings, observations of the flame are made with a disappearing-filament type of optical pyrometer, gas temperatures are measured by velocity thermocouples, and the gases are sampled and analyzed for the usual constituents and for water vapor and solid content. In some tests, water-cooled heat-flow meters, the face of which is a corrugated stainless-steel disk of about 1-1/2 in. diam, have been installed in the walls. The rate of heat absorption is measured by the temperature gradient in the steel disk. Air blown across the face of the disk is designed to prevent transfer of heat to the disk by convection. Based on essentially the same principle of measurement of the rate of heat absorption by the temperature gradient, another instrument has been used for the study of convection in the flame.

Because of the high degree of ingenuity that has gone into the development of the various instruments used in this work, it is regretted that, in the interest of brevity, descriptions must be omitted. The reader who is interested is referred to the British and French publications of the work that are cited in the references.

PLAN OF EXPERIMENTS

Two general classes of tests have been made: (a) "performance" or "industrial" tests, and (b) "combustion mechanism" or "scientific" tests. The purpose of the performance tests is to determine the effects of certain variables, such as type of fuel, type of burner, type of atomizing agent, degree of mixing of air, excess of air, or rate of heat input upon the radiating characteristics of the flame. It is to be expected that the results of such tests can be immediately applicable in industrial furnaces. Seven series of performance tests, each series consisting of many separate tests, had been completed through 1955.

TABLE 1. CONDITIONS AND VARIABLES OF TESTS THROUGH 1955

VARIABLES	Performance Tests						Combustion-Mechanize Tests		
	1 ^{3,4,5}	2 ^{6,7}	3 ^{8,9}	4 ^{8,9}	5 ^{8,9}	6 ¹⁰	7 ¹⁰	11	12
Fuel	(a) Heavy fuel oil (b) Creosote-pitch	Heavy fuel oil	Coke-oven gas and fuel oil	Coke-oven gas and fuel oil	Coke-oven gas, fuel oil, and creosote-pitch	(a) Heavy fuel oil (b) Light fuel oil (c) Creosote oil	(a) Heavy fuel oil (b) Coke-oven gas	Heavy fuel oil	(a) Coke-oven gas (b) Coke-oven gas + propane (c) Light fuel oil (d) Heavy fuel oil
Rate of heat input, million Btu/hr	(a) 7.6 (b) 10.6	(a) 5.5 (b) 9.9	(a) 6.8 (b) 10.4	8.7	8.7	7.1	4.4	7.6	6.0
Atomizing agent	(a) Steam (b) Air	(a) Steam (b) Air	Steam	Steam	Steam	(a) Steam (b) Air	-	(a) Steam (b) Air	Air
Rate of supply of atomizing agent, lb/lb fuel	Steam, 0.36 to 0.56 Air, 0.53 to 0.81	(a) 0.2 (b) 0.5	-	-	-	-	-	Steam, 0.3 Air, 0.5	Light oil: (a) 0.46 (b) 0.73 Heavy oil: (c) 0.44
Thrust on burner, lb	-	-	(a) 1.3 (b) 2.5 (c) 2.6 (d) 5.0	3.3	3.96	(a) 2.2 (b) 4.4, air at side of furnace (c) 4.4, air around burner	(a) 2.2 (b) 3.3	-	(a) 2.6 (b) 4.8
Type of burner	-	Five types of burners	-	-	-	-	-	-	-
Excess of air at furnace exit, per cent	(a) 58 (b) 70	-20	(a) 0 (b) 40	8 to 10	9 to 11	-	(a) 10 (b) 40	Steam, 15 Air, 65	0 to 16
Carbureting agent	-	-	Heavy fuel oil	Heavy fuel oil	(a) Heavy fuel oil (b) Creosote-pitch	-	-	-	-
Amount of carburant, per cent	-	-	(a) 0 (b) 15.0	(a) 0 (d) 60 (b) 20 (e) 80 (c) 40 (f) 100	(a) 0 (b) 33.3 (c) 66.7 (d) 100.0	-	-	-	-
Temperature of combustion air, F	-	-	-	-	-	-	(a) 212 (b) 1200	-	-

* Reference to publications giving results of tests.

□ Blocks with heavy borders indicate variables of test series.

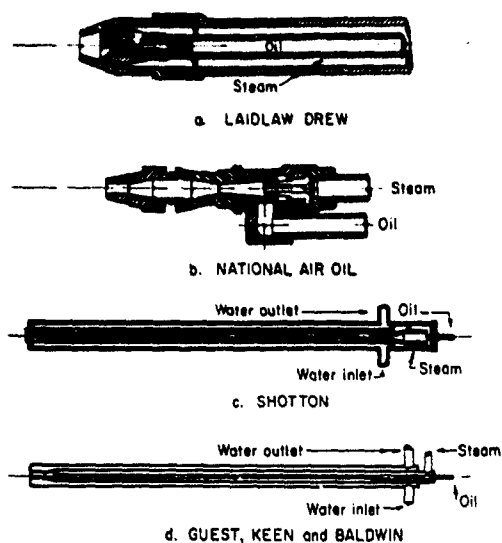


FIGURE 6. FOUR OIL BURNERS USED IN PERFORMANCE TEST 2

The purpose of the combustion-mechanism tests is to examine a few flames in considerable detail. For example, the rate of mixing and the appearance and disappearance of carbon in the flame are studied both longitudinally and laterally and, by measuring the radiation of small elements of the flames, an attempt is made to relate the carbon content and the radiating characteristics of the flame. Only two series of these tests have been made.

The factorial method of planning the experiments has been used in all series of tests. Thus, in a series of tests of five variables, 32 separate tests were so selected as to give all combinations of high and low values of each variable from which not only the effect of the high and low levels could be obtained but also the interaction of the several variables.

The data have been analyzed statistically and the confidence level of each derived data point has been calculated. As the tests were run through two shifts, with the third shift being used to make necessary adjustments to equipment, the tests have been so planned as to enable a calculation of the effects, if any, of the three teams of men used to obtain the data.

Variables Investigated

Table 1 summarizes the variables that have been investigated in the seven series of performance tests and the two series of combustion-mechanism tests that had been made up to the end of 1955. A total of ten variables has been studied. In some series, only one variable was studied at several different values or levels; in the first series, the effects of five different variables were determined. Those factors that were used as variables in each series are de-

TABLE 2. CHARACTERISTICS OF FUELS

	Residual Oil			Light fuel oil	Creosote-pitch	Creosote-oil	Coke-oven gas, vol. per cent.
	1	2	3				
Density, 60 F	0.952	0.982	0.981	0.826	1.140	0.998	CO ₂ , 2.1
Saybolt universal viscosity, 100 F, sec	1750	960	1130	34	1120 ±	27	CN ₂ , 2.0
Conradson carbon, %	8.1	13.85	-	-	22.7	-	O ₂ , 0.3
Asphaltenes, %	3.25	7.60	-	-	19.5	-	CO, 8.2
Initial boiling point, F	-	-	385	360	-	417	H ₂ , 49.5
Boiling point for 70%, F	-	-	968	530	-	511	CH ₄ , 26.8
Final boiling point, F	-	-	-	575	-	615	N ₂ , 11.1
Composition, %							Total 100.0
Carbon	84.6	-	86.8	85.0	89.8	88.0	
Hydrogen	11.5	-	10.2	13.4	5.7	8.3	
Oxygen	-	-	1.0	0.5	-	2.2	
Sulfur	3.5	-	1.9	0.9	0.8	0.01	
High heat value, Btu/lb	18,675	18,270	-	-	16,490	-	4842
Ratio: C/H	7.35	-	8.5	6.3	15.8	10.6	2.18

1- At 122 F
2- Btu/cu ft

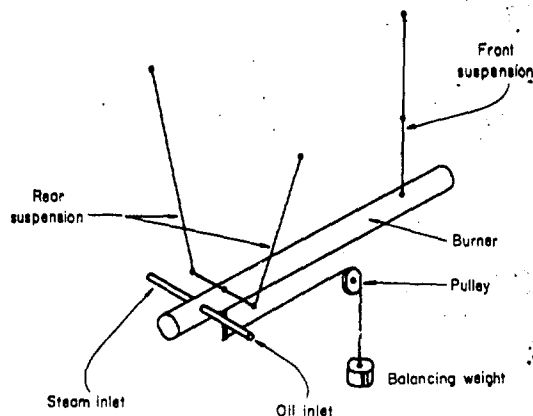


FIGURE 7. SETUP FOR MEASURING THRUST OF BURNERS

signated by a heavy border around the applicable blocks.

As one of the most important factors that govern the radiation from the flame, the type of fuel has been subject to intensive investigation, both as single fuels of different types and as mixtures.

Characteristics of Fuels Used

Table 2 presents data on the characteristics of the fuels that have been used in the tests.

Although complete data are not given for all fuels on the same basis, the data do give a picture of the class of the fuels. The oils are from the Middle-East fields. Shipments obtained varied somewhat in viscosity, in Conradson carbon, and C/H ratio. The light fuel oil would be classed in the U. S. as a No. 2 oil.

The creosote-pitch was stated to be a blend of the creosote-oil fraction of coal tar boiling

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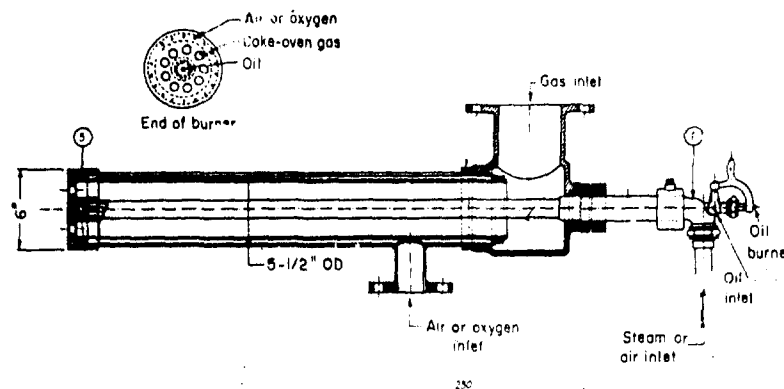


FIGURE 8 BURNER USED FOR GAS OR FOR GAS AND LIQUID FUELS

between 535 and 680 F and the pitch, the residue above the latter temperature. The ratios used have been 50-50 and 40 per cent creosote oil and 60 per cent pitch. The creosote oil used alone was, from its boiling range, a slightly lighter fraction than that said to have been used in the blend.

The coke-oven gas was that from the ovens at the steel plant used for the production of blast-furnace coke.

Burners Used

Fig. 6 shows four of the burners used in the series of tests of burners. They include external mixing and internal mixing both at the front and the back.

The oil was supplied to the burners at pressures slightly above those of the atomizing agent. Air or steam was supplied at a pressure of 10 to 100 psi as required by the amount of atomizing agent used. Early in the work, the amount of atomizing agent was expressed as the ratio of the weight of the agent to that of the fuel. Because one of the most important effects of the rate of supply of atomizing agent appeared to be that on the rate of mixing of the fuel and air, in test series 3 and following, the thrust of the burner when feeding fuel and atomizing agent was measured. Fig. 7 shows the arrangement by which the thrust was measured. The burner was suspended by three wires and a wire attached to the lower part of the burner passed over the pulley to support a pan on which weights were placed to balance the thrust. It was possible to measure the thrust within 20 g in a total of 1000 g, or 2 per cent. The thrust is taken as a measure of the momentum of the jet, a most important factor in the mixing of the fuel and air.

Fig. 8 shows the type of burner used for gas alone or for gas with oil. The raw gas issued from the row of ports around the central

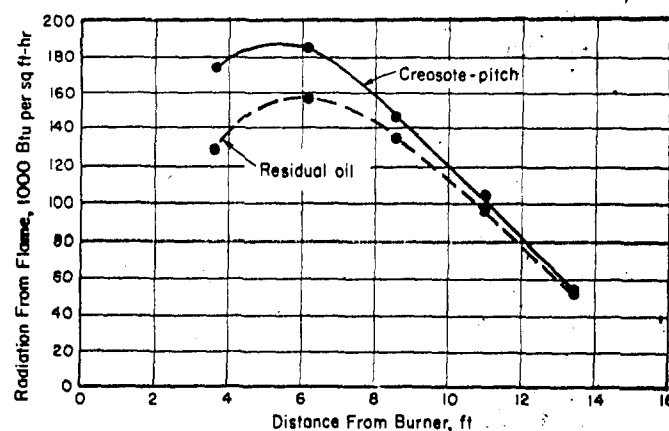


FIGURE 9. RADIATION FROM FLAMES OF RESIDUAL OIL AND BLEND OF 40 PER CENT CREOSOTE OIL, 60 PER CENT PITCH

Performance Test No. 1

oil-burner nozzle. A special replaceable plate was made for the gas ports to facilitate changing the thrust while maintaining the same delivery of gas. Air or oxygen could be supplied through the outer row of ports.

HIGHLIGHTS OF RESULTS OBTAINED

Because of the great number of data obtained from the research over the years, no attempt will be made in this paper to present more than certain highlights. The interested reader can consult the published British and French papers for the details.

Effect of Type of Fuel on Radiation from Flame

Fig. 9 shows data obtained from the first series of tests that prove the important effect that the type of fuel can have on the radiation from the flame. The ordinate is the radiation in Btu per sq ft-hr from the flame alone, that is, with a cold back wall. The shapes of the curves for the flames of residual oil and the

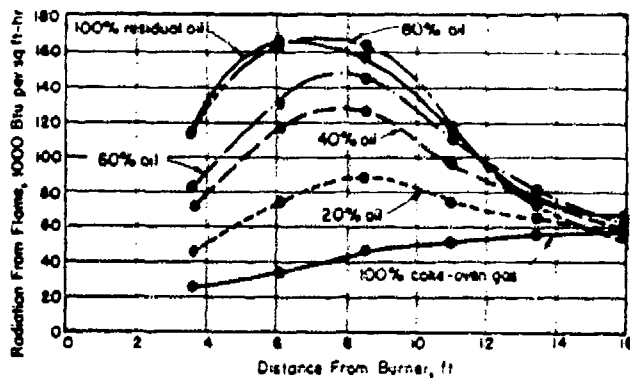


FIGURE 10. RADIATION FROM FLAME OF COKE-OVEN GAS CARBURETTED WITH VARYING PERCENTAGES OF RESIDUAL OIL

Performance Test No. 4

creosote-pitch blend are similar, reaching a maximum at about 5 ft from the burner. Under the method of calculation from the raw data, the effects of other variables are eliminated. At the maximum, the radiation from the creosote-pitch, which had about three times the Conradson carbon, six times the asphaltene content, and about twice the C/H ratio of the residual oil, was about 20 per cent higher than that from the residual oil. Although, at the last point of measurement, however, at about 14 ft from the burner, the radiation was the same for the two fuels, yet the total radiation from the creosote-pitch blend was greater than that from the residual-oil flame.

Figs. 10 and 11 show the radiation from flames of coke-oven gas alone, of coke-oven gas carburetted with varying percentages of residual oil, and of the creosote-pitch blend. The percentages of each fuel are calculated on the basis of the heat value that each contributes to the total. The coke-oven gas burned with an essentially non-luminous flame and its radiation was that only of the CO_2 and H_2O content. The radiation increased substantially uniformly along the length of the flame as mixing and combustion progressed.

Fig. 10 shows that a substantial increase in radiation from the flame is obtained by the addition of 20 per cent of oil and that further increases in carbureting oil continue to increase the radiation. Both Figs. 10 and 11 show that, as compared with 100 per cent liquid fuel, one third to 40 per cent of the heat value of residual oil can be replaced by a weakly radiating coke-oven gas without a great decrease in radiation from the flames. With a larger furnace and thicker flame, the decrease in radiation with a given replacement of fuel oil by gas

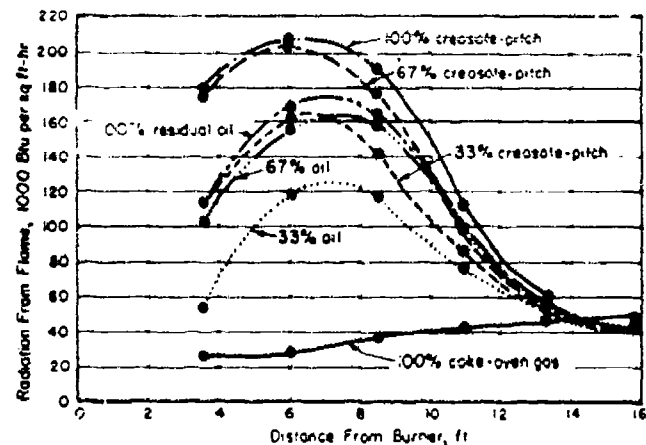


FIGURE 11. RADIATION FROM FLAME OF COKE-OVEN GAS CARBURETTED WITH RESIDUAL OIL AND BLEND OF CREOSOTE AND PITCH

Performance Test No. 5

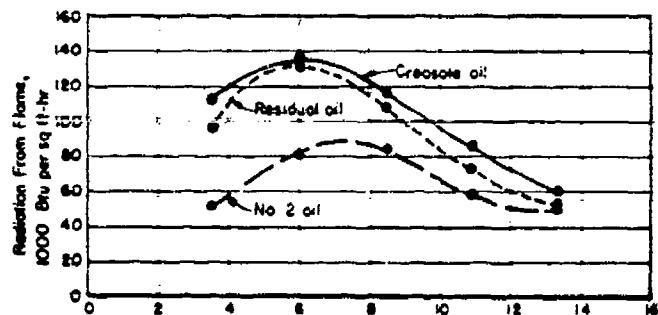


FIGURE 12. RADIATION OF FLAMES OF CREOSOTE OIL, RESIDUAL OIL, AND NO. 2 OIL

Performance Test No. 6

would not be as great as observed here.

Both Figs. 10 and 11 also show that the radiation at the last point of measurement is not greatly different for any of the fuels or blends.

Fig. 12 presents data obtained in performance test No. 6 for three widely different liquid fuels, No. 2 oil, residual oil, and creosote oil. Although its viscosity was about the same as that of the No. 2 oil, the creosote oil gave a substantially higher radiation than did the light petroleum oil and higher, in fact, than did the residual oil. Yet again, the close approach of the values for radiation of the three fuels at the tail of the flames can be seen.

Emissivities and Temperatures of Flames

Fig. 13 shows the emissivities and temperatures, as derived by the Schmidt method, for four of the flames whose radiation was shown in Fig. 11. The temperatures of the creosote-

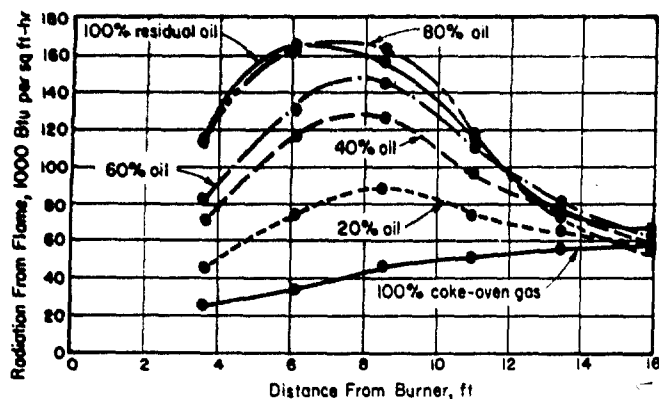


FIGURE 10. RADIATION FROM FLAME OF COKE-OVEN GAS CARBURETTED WITH VARYING PERCENTAGES OF RESIDUAL OIL

Performance Test No. 4

creosote-pitch blend are similar, reaching a maximum at about 5 ft from the burner. Under the method of calculation from the raw data, the effects of other variables are eliminated. At the maximum, the radiation from the creosote-pitch, which had about three times the Conradson carbon, six times the asphaltene content, and about twice the C/H ratio of the residual oil, was about 20 per cent higher than that from the residual oil. Although, at the last point of measurement, however, at about 14 ft from the burner, the radiation was the same for the two fuels, yet the total radiation from the creosote-pitch blend was greater than that from the residual-oil flame.

Figs. 10 and 11 show the radiation from flames of coke-oven gas alone, of coke-oven gas carburetted with varying percentages of residual oil, and of the creosote-pitch blend. The percentages of each fuel are calculated on the basis of the heat value that each contributes to the total. The coke-oven gas burned with an essentially non-luminous flame and its radiation was that only of the CO_2 and H_2O content. The radiation increased substantially uniformly along the length of the flame as mixing and combustion progressed.

Fig. 10 shows that a substantial increase in radiation from the flame is obtained by the addition of 20 per cent of oil and that further increases in carbureting oil continue to increase the radiation. Both Figs. 10 and 11 show that, as compared with 100 per cent liquid fuel, one third to 40 per cent of the heat value of residual oil can be replaced by a weakly radiating coke-oven gas without a great decrease in radiation from the flames. With a larger furnace and thicker flame, the decrease in radiation with a given replacement of fuel oil by gas

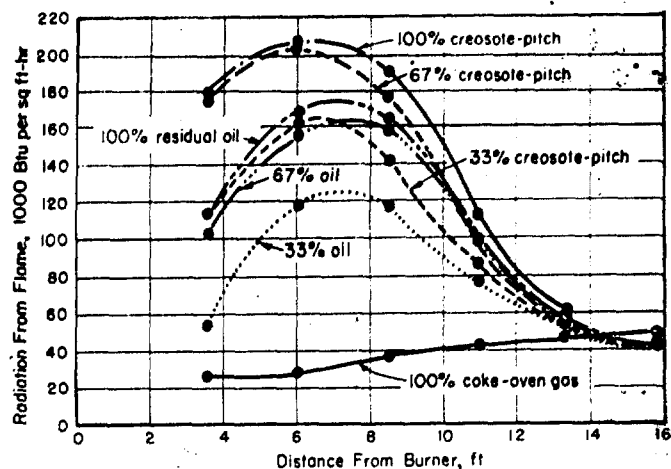


FIGURE 11. RADIATION FROM FLAME OF COKE-OVEN GAS CARBURETTED WITH RESIDUAL OIL AND BLEND OF CREOSOTE AND PITCH

Performance Test No. 5

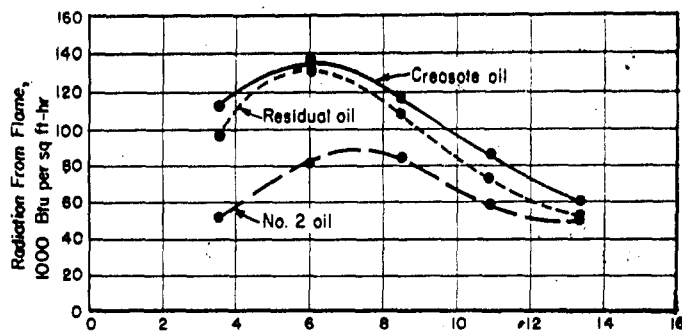


FIGURE 12. RADIATION OF FLAMES OF CREOSOTE OIL, RESIDUAL OIL, AND NO. 2 OIL

Performance Test No. 6

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Both Figs. 10 and 11 also show that the radiation at the last point of measurement is not greatly different for any of the fuels or blends.

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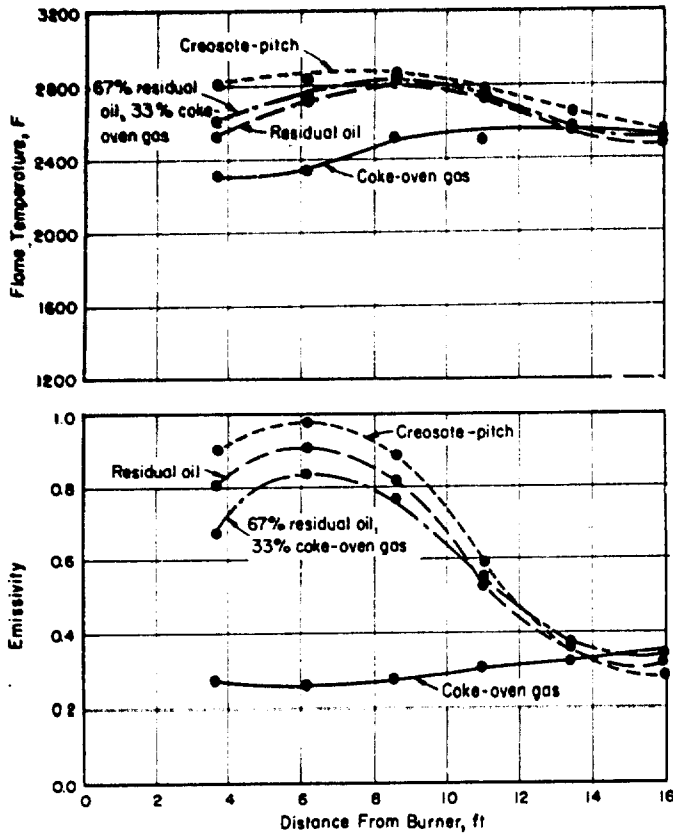


FIGURE 13. TEMPERATURE AND EMISSIVITY, DERIVED BY SCHMIDT METHOD, OF FLAMES OF COKE-OVEN GAS, RESIDUAL OIL, CREOSOTE-PITCH, AND GAS CARBURETTED WITH OIL

Performance Test No. 5

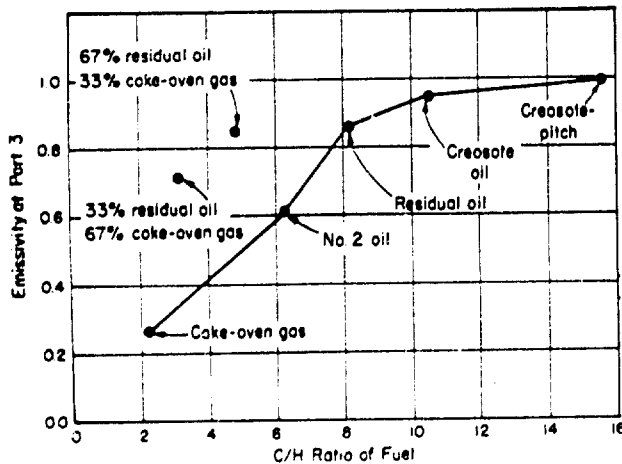


FIGURE 14. RELATION OF EMISSIVITY OF FLAME AND THE C/H RATIO IN THE FUEL

pitch, residual oil, and oil-carburetted flames were closely the same after the second position of measurement. Their emissivities differed more than did their temperatures and these differences in emissivity were thus the principal reasons for differences in radiation evident in

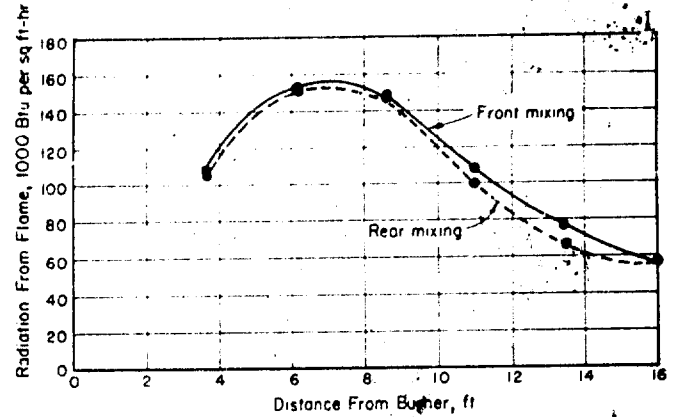


FIGURE 15. RADIATION OF OIL FLAMES OF FRONT MIXING AND REAR MIXING BURNERS

Performance Test No. 2

Fig. 11. As the carbon is burned, the emissivities approach those for flames containing only CO_2 and H_2O . The temperature of the flame of the coke-oven gas is surprisingly low in the early part of the flame and its emissivity surprisingly high for a completely nonluminous flame particularly in the latter part of the flame. Calculation, from the data of Hottel, et al, on the emissivity of CO_2 and H_2O , whose contents for the coke-oven gas flame were 7.7 and 20.0 per cent, respectively, gives an emissivity of 0.21 at the final temperature of 2500 F indicated in Fig. 13 as compared with the derived value of 0.345 shown in the figure. If the true temperature were actually higher, as suspected, the emissivity would be somewhat lower than 0.21.

The Schmidt method of derivation of emissivity and temperature of the flame is strictly applicable only to gray flames and nonluminous gas flames are not gray. This problem will undoubtedly have further attention in the experimental research at IJmuiden.

Further in regard to the temperature shown in Fig. 13, it is to be realized that, derived as they were, they are averaged radiant temperatures across the width of the flame. The temperature of the flame obviously varied across the furnace and maximum temperatures higher than 2800 + F shown for the creosote-pitch, for example, occurred in the furnace.

Fig. 14 presents a curve taken from a recent paper by Rivière (10). This curve shows the relation of the emissivity of the flame at Port 3, which is essentially the maximum, for coke-oven gas and four liquid fuels to the C/H ratio of the fuels. The data come from performance tests nos. 3 to 6. For these individual fuels, including even the blend of creosote and pitch,

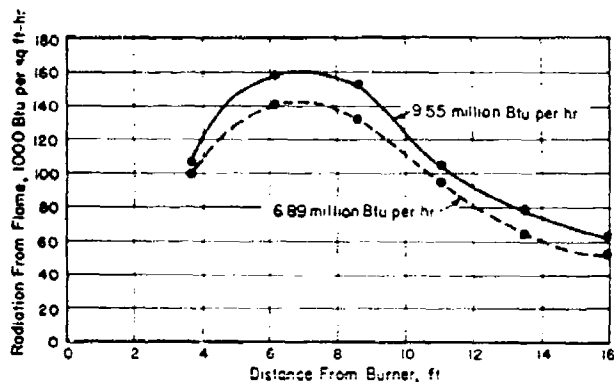


FIGURE 19 RADIATION OF FLAMES AT TWO RATES OF HEAT INPUT
Performance Test No. 2

steam or air. The underlying reason is undoubtedly connected with the less rapid mixing of the combustion air by the reduced momentum of the jet when less atomizing agent is used.

Fig. 18 presents further data on the effect of amount of atomizing agent and on the method of admission of the combustion air. Data are given for three fuels as obtained in performance test No. 6 and reported by Rivière (10).

The rate of supply of atomizing agent is here expressed as the thrust on the burner. Comparison of the two lower sets of curves at 2.2 lb and 4.4 lb of thrust, when the combustion air was admitted at low velocity on either side of the furnace, as normally used in the tests, shows that the radiation from the flame of the No. 2 oil was greatly reduced over the entire length of the flame when the amount of atomizing agent was increased. At the greater thrust, the maximum radiation for the residual oil and creosote oil moved toward the burner but the maximum was not greatly reduced. The radiation from these fuels was materially reduced beyond 8 ft from the burner.

The top set of curves shows that the combination of high thrust and the admission of combustion air through the "dog house" directly around the burner at high velocity resulted in a flame of No. 2 oil with radiating characteristics similar to those shown in Figs 10 and 11 for coke-oven gas. The creosote oil was only slightly more radiant. The residual oil still displayed the familiar peak of 6 ft from the burner but this peak was less than half as high as with the admission of combustion air at low velocity.

The fact that the high momentum of the jet and the high-velocity combustion air had more effect on the creosote oil than on the residual

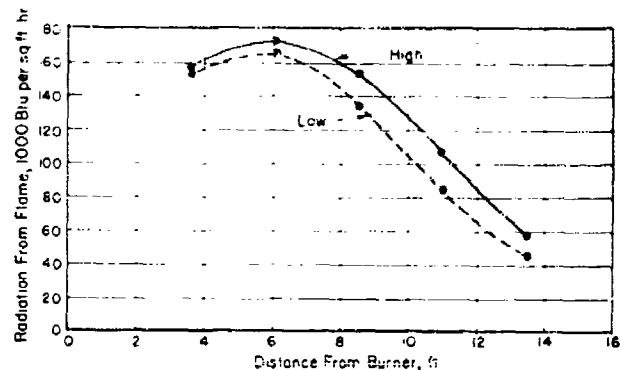


FIGURE 20 RADIATION OF OIL FLAMES WITH VARYING AMOUNTS OF EXCESS AIR
Performance Test No. 1

oil is of considerable interest. Under less extreme conditions of mixing as shown in the two lower sets of curves and in Fig. 12, the radiation of the flame of creosote oil was shown to be higher than that of residual oil.

Effect of Rate of Heat Input

Fig. 19 presents data on the radiation of flames in performance test No. 2 at two different rates of heat input to the furnace. Quite as to be expected, the radiation is greater at the higher rate of heat input along the entire length of the flame although it is less marked at the first observation port. The detailed data show that the emissivity of the flames at the peak of their radiation did not differ much with rates of heat input in this test; hence, the greater radiation at that point resulted largely from the higher temperature of the flame as the rate of firing was greater. In general, however, later experiments showed that away from the peak, as even at the peak when small rates of heat input are used, the variation of the emissivity accounted for a substantial part of the variation in radiation.

Effect of Excess Air

Fig. 20 shows that the radiation decreased as the excess of air supplied for combustion increased. The differences were not great, 58 per cent excess for the low and 70 per cent for the high. The data are from performance test No. 1 in which full control over inleakage of air into the furnace had not been obtained as was possible in later tests.

Relation of Radiant Characteristics of Flame to Heat Transfer

The presentation of the results that has

been made up to this point in the paper has dealt solely with the effect of the several variables on the rate of radiation and the temperature and emissivity of the flame at various points along the length of the flame. The ultimate objective of a search for knowledge on radiation from flames must obviously go beyond the establishment of these relations and must include the establishment of an understanding of the effect of the variables on the rate of heat transfer to "work" in the furnace. This "work" might be steel as in an open hearth, billets as in a reheating furnace, water-filled or oil-filled tubes as in a steam generator or an oil still, cement in a kiln, or glass in a glass tank.

In the experimental furnace for gas and oil at IJmuiden, the only load comprises the heat absorbed by water-cooled ports and probes, and the radiation from the outer walls of the furnace. Because this load on the furnace remains substantially constant in all tests, the inside temperature of the walls furnishes a certain measure of the rate of heat transfer to the wall. Also, because the Schmidt method for calculation of the emissivity of the flame requires the measurement of this temperature and a calculation of the radiation from the walls, the data on wall radiation are available from all series of tests except that of performance test No. 1.

In addition, from Tests 3, 4, and 5, data are available for the heat absorption of the calorimeters, or heat-flow meters, which have been briefly described; thus, another measure of the heat delivered by the flame is available.

Fig. 21 presents in the top section the radiation from the flames of three fuels differing substantially in their radiant characteristics. These have already been shown in Fig. 11. In the middle section is given the data for the radiation of the walls, and in the bottom section that for the heat absorbed by the calorimeters. The similar shape of the wall radiation and calorimeter curves is evident. The values are also of similar order, but the calorimeter values are somewhat the greater.

Two points are striking in a comparison of the radiation of the flame with either of the measures of heat delivered to the furnace walls. The first is that, although the flame radiation curves differ widely for the three fuels, the heat delivered to the walls obviously differs much less among the fuels. The second is that, although the peak of flame radiation occurs at 6 to 7 ft from the burners, with the liquid fuels, there is no similar peak in the rate of heat delivery to the walls. The curves rise sub-

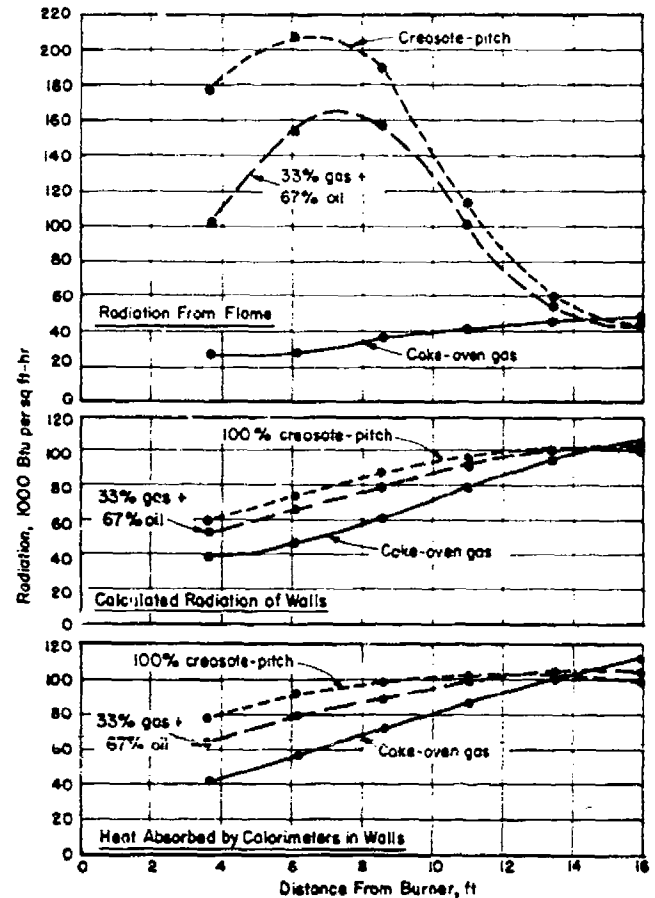


FIGURE 21. COMPARISON OF RADIATION FROM FLAMES AND INDICATIONS OF HEAT DELIVERED TO FURNACE WALLS
Performance Test No. 5

stantially uniformly along the length of the furnace for all three fuels.

The explanation for the latter fact is undoubtedly first that longitudinal radiation from the flame to the walls and from the walls in one part to the walls in other parts tends toward uniformity of the wall temperature, and, second, that the flame is a cone and not a cylinder. Furthermore, convection undoubtedly plays a considerable part in fixing the wall temperature. Near the burner, heat is transferred from the walls to the combustion air that enters at the front and flows between the walls and the expanding jet of flame. In the rear part of the furnace, where the mixing and combustion are nearing completion and the flame sweeps the walls, the transfer of heat by convection from the high-temperature gases must add materially to the transfer of heat by radiation.

To arrive at some numerical measure of the relative total rate of transfer of heat from

the flame, the areas under the curves of radiation from the flame of Fig. 21 have been measured by a planimeter. Similarly, the areas under the curves of the radiation of the walls and of those of the calorimeter measurements have been measured. It is recognized that this integration for the radiation of the flames is in error because the diameter of the flames and thus the area of each unit of length is not constant along the length of the flame. However, lacking data on the contour and area of the flames, they are all treated as cylinders.

The results of the integrations follow:

Radiation from flame

$$\text{Ratio- } \frac{\text{Creosote-pitch}}{\text{Coke-oven gas}} = 3.60$$

$$\text{Ratio- } \frac{\text{Gas-oil}}{\text{Coke-oven gas}} = 2.88$$

Wall Radiation from Wall Temperatures

$$\text{Ratio - } \frac{\text{Creosote-pitch}}{\text{Coke-oven gas}} = 1.24$$

$$\text{Ratio - } \frac{\text{Gas-oil}}{\text{Coke-oven gas}} = 1.19$$

Wall Radiation from Calorimeters

$$\text{Ratio - } \frac{\text{Creosote-pitch}}{\text{Coke-oven gas}} = 1.23$$

$$\text{Ratio - } \frac{\text{Gas-oil}}{\text{Coke-oven gas}} = 1.17$$

These calculations show that, whereas the flame-radiation data indicate that the creosote-pitch and gas-oil flames had potential radiating powers 3.6 and a.88 times, respectively, that of the coke-oven gas flame, the data on the heat absorbed at the walls indicate that with the creosote-pitch and oil-gas flames this was only 24 to 19 per cent more than that with the coke-oven gas flame. This calculation does not, it

is again emphasized, allow for the difference in area of the flame along the length of the furnace. However, it does suggest that convection must have played an important part in the transfer of heat in the furnace.

Although these integrations have been carried out only on these three flames, inspection of all the published data from the IJmuiden tests clearly indicates that although an increase in measured radiation from the flames is always reflected in an increased transfer to the walls, the increase to the walls is less than proportional to that from the flames.

The conclusion to be drawn from these comparisons is that, because a given increase in radiation of the flame does not give a corresponding increase in the transfer to the "work," further research on all the factors affecting both radiation and convection in furnaces is of great importance. Also, these results emphasize the important contribution that will be made to the knowledge of heat transfer by radiation when "work" in the form of water tubes or other materials is placed in the IJmuiden furnace to obtain definite and unquestioned information on the useful rate of heat transfer in various parts of the furnace.

Effect of Preheating Combustion Air

The statistical analysis of the data from performance test No. 7 has not yet been completed. Rivière has presented, however, the highlights of the effects of the four variables studied in this test series. Because the preheat of the air for combustion was the variable studied in this series that had not been previously investigated, the following relevant conclusions are quoted from Rivière's paper (10).

"An increase in the temperature of the combustion air from 212 F to 1200 F changed only slightly the initial conditions of mixing of the fuel and air, but slowed up the mixing at the end of the flame. The result was an increase of about 10 per cent in the distance required to obtain a stoichiometric mixture.

"For residual-oil flames, the change in the temperature of the air modified neither the content of carbon particles in the flame nor the total emissivity of the flame. In contrast, the emissivity of the coke-oven gas flames decreased by five to ten per cent when the air temperature was increased.

"The temperatures of the flames and of the walls were the two dependent variables the most greatly influenced by the increase in the temperature of the combustion air. Thus, the temperature of the gas on the axis of the flame was

increased on the average 260 F with an increase of 990 F in the temperature of the air."

Combustion-Mechanism Tests

As previously stated, the purpose of the combustion-mechanism tests had been to study the process of mixing in the flame, the process of combustion, with particular reference to the content of free carbon in the gas, and to relate these data to the temperature, the radiation, and the emissivity of the flames. In the first series of tests, the difficult procedure for the quantitative determination of the carbon in the gas was not completely successfully developed but it was for the second series. No attempt will be made in this paper to summarize the results of these two tests. References 11 and 12 give analyses of the principal findings.

SUMMARY

The international co-operation in industrial research on heat transfer by radiation from flames that is being carried out by the International Flame Research Foundation at IJmuiden and at cooperating laboratories has produced and is producing much valuable information on an incompletely understood subject. The present paper has touched on the highlights of the methods of research and the instrumentation that has been developed. The effects of the characteristics of the fuels used, the types of burners, the rate of firing, the type of atomizing agent, the method of mixing of combustion air, the amount of excess air, and the temperature of the combustion air have been touched upon. The need for further information on the relation between the radiating power of flames and the heat transferred to the work has been emphasized. It is hoped that an interest has been stimulated in the readers to study the detailed reports and to follow the future work.

Acknowledgements

Emphasis is again to be placed on the fact that the data presented in this paper, with little attempt at original interpretation by the author, have resulted from a vast amount of planning, arduous work in experimentation, and detailed analysis of the data by many European scientists and engineers.

Particular thanks are owing to Prof. J. E. de Graaf, IJmuiden, to Monsieur Michel Rivière, French Institute for Iron and Steel Research, Paris, and for several years Principal Investigator at IJmuiden, to Dr. Marcel Michaud of Air Liquida, Paris, and Secretary of the French Committee, and to Professor M. W. Thring, Sheffield,

who carefully reviewed the original draft of this paper and made many valuable suggestions for its improvement.

Acknowledgement is also made to those members of the American Committee who made helpful suggestions on the original draft, and to the group at Battelle, H. R. Hazard, W. R. Keagy, Jr., W. T. Reid, H. W. Russell, and C. E. Sims, who closely follow the research and who critically reviewed the paper.

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